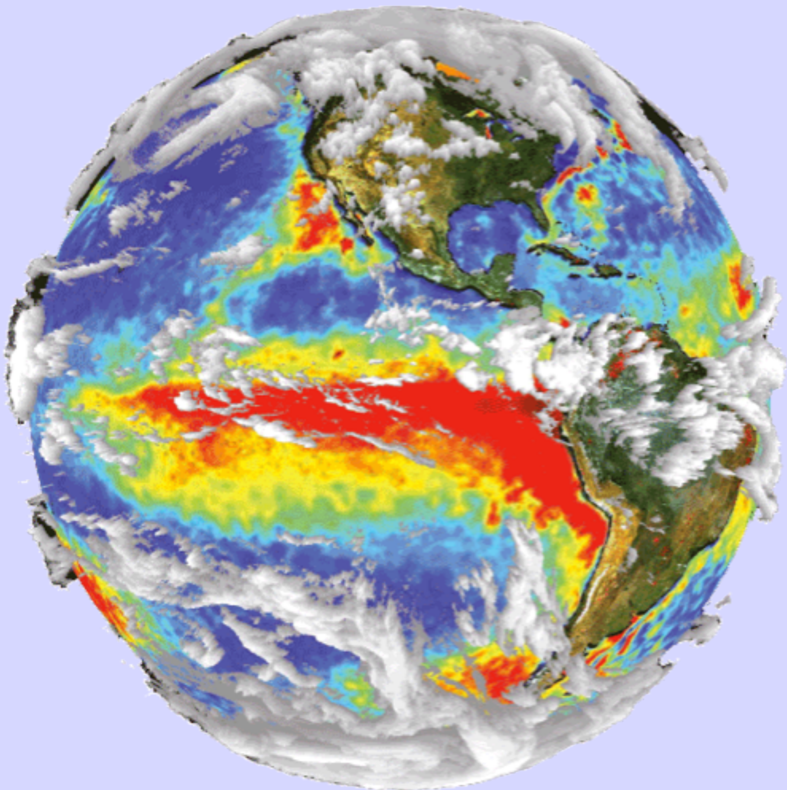
Understanding ENSO in climate models: from statistics to process-based metrics



Eric Guilyardi

IPSL/LOCEAN, Paris

NCAS-Climate, University of Reading

Seasonal Prediction Webinar - Oct. 2014

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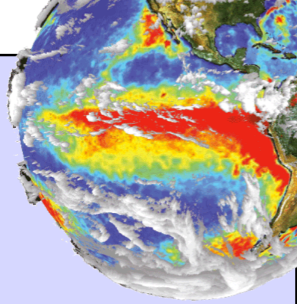


ENSO in CMIP simulations

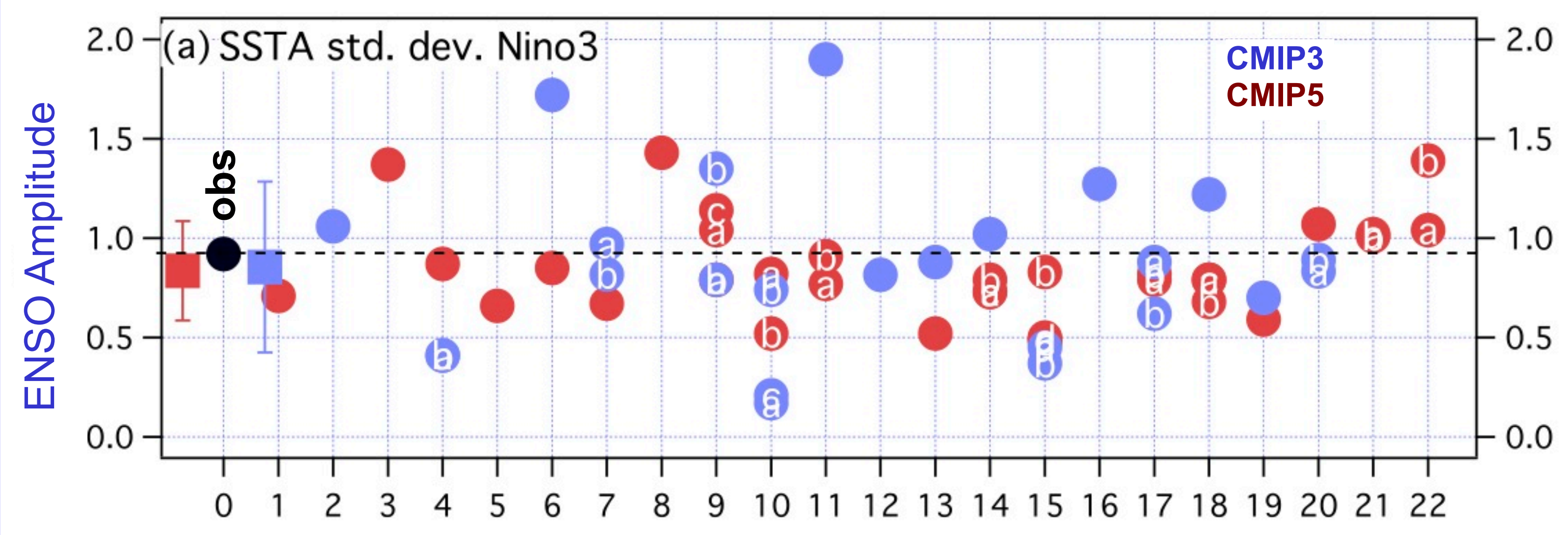
Outline:

- ENSO statistics – from CMIP3 to CMIP5
- Mean state in the Tropical Pacific
- ENSO in a warming climate
- Process-based ENSO evaluation, focus on atmosphere

- This talk:
  - Mean state and ENSO statistics in CMIP are improving and new robust information about ENSO in the future
  - But process-based performance still an issue

El Niño in coupled GCMs - amplitude

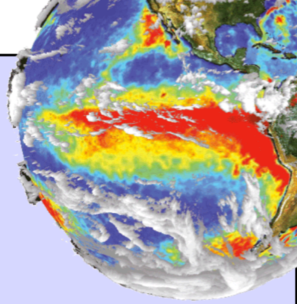
Standard deviation SSTA (C) in Niño3

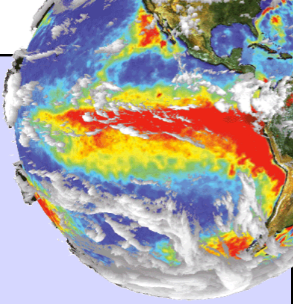


Modelling centers

- ENSO amplitude in CMIP3: very large diversity of simulated amplitude
- Range reduced in CMIP5 (improved mean state ? tuned in modelling development process ?)

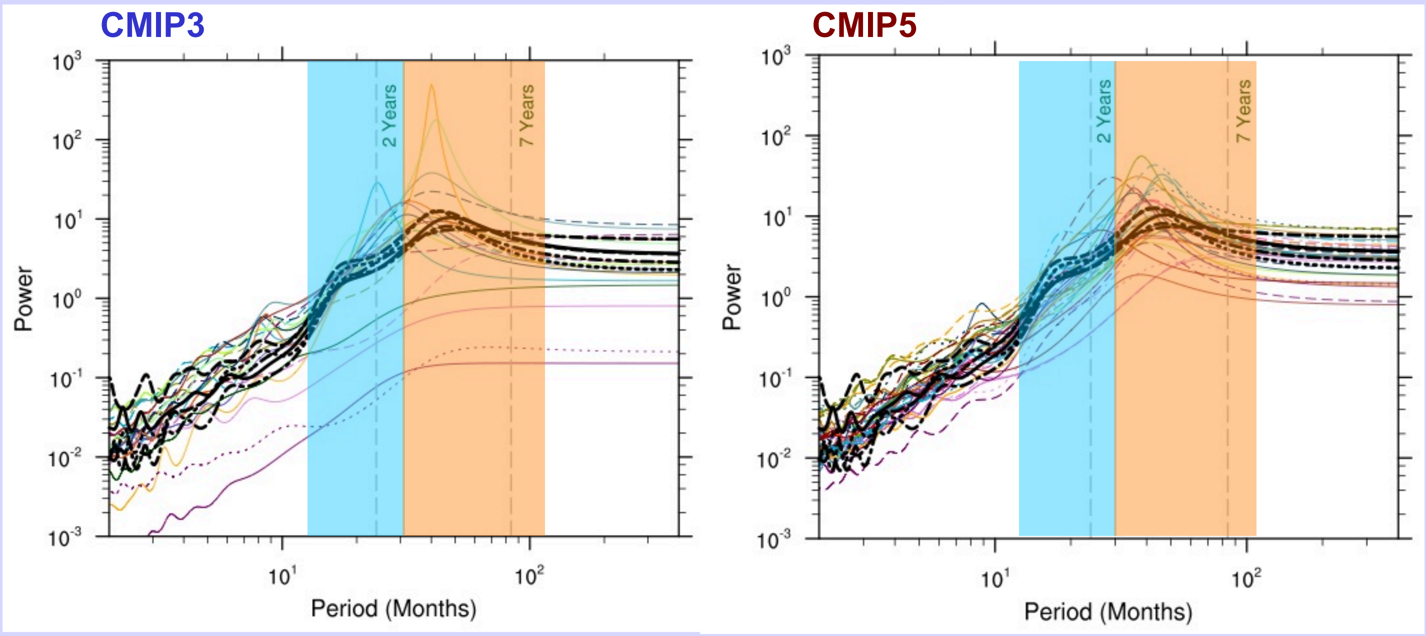
Bellenger et al. (2013)



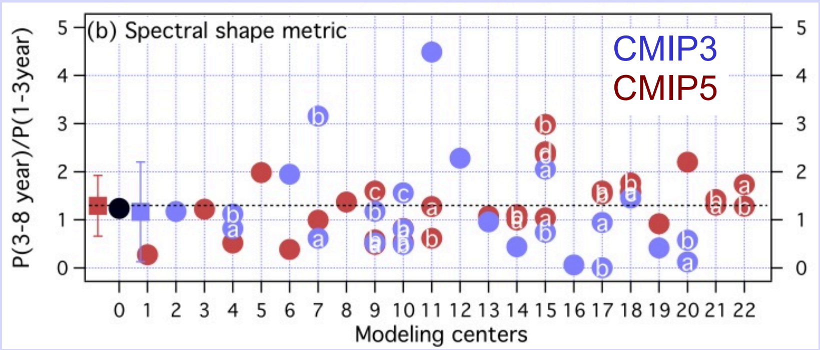


El Niño in coupled GCMs - frequency

Niño3 SSTA spectra



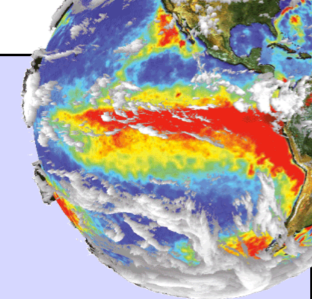
Courtesy K. AchutaRao

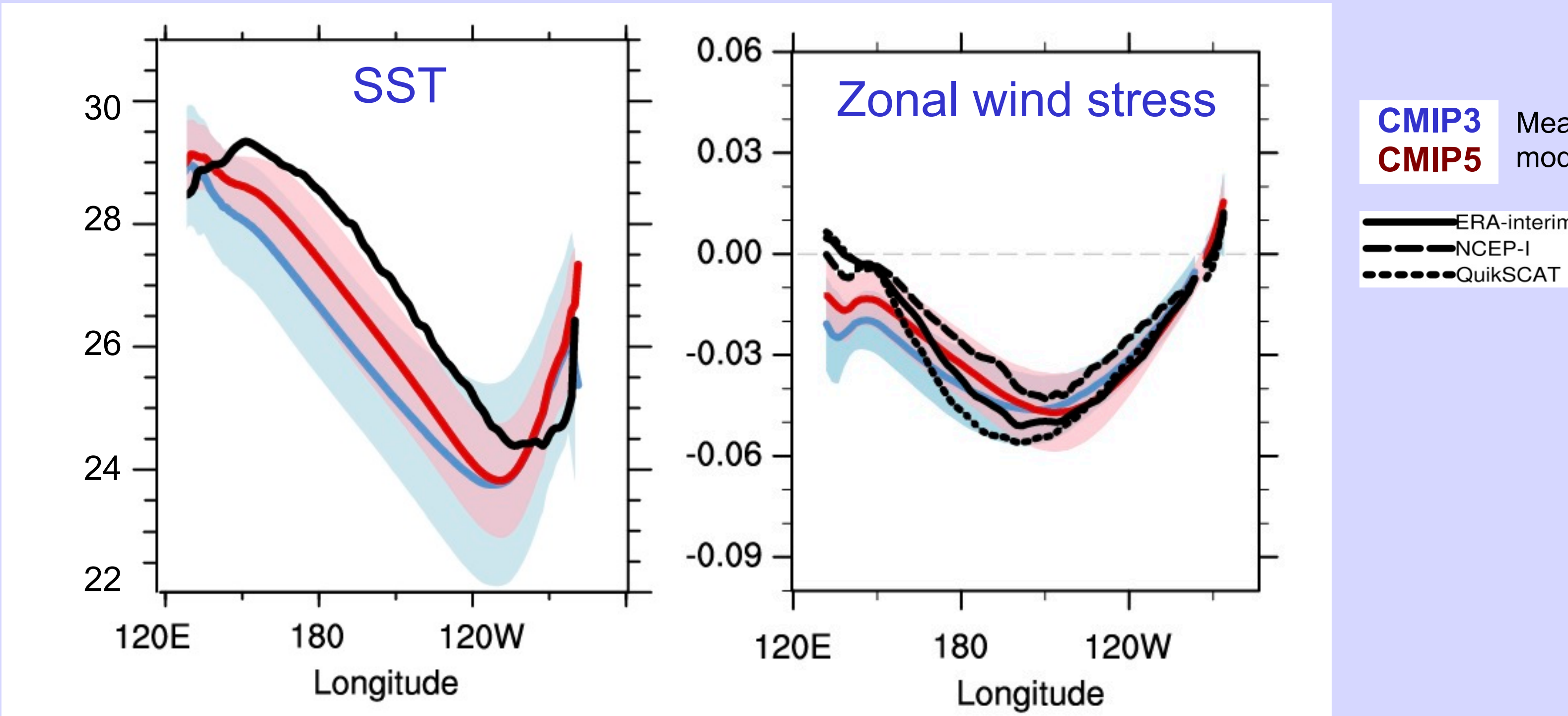


- Improved spectra in CMIP5
- No more models with no ENSO
- Shift towards lower frequency as in obs

Bellenger et al. 2013

Mean equatorial SST and zonal wind structure in CMIP models

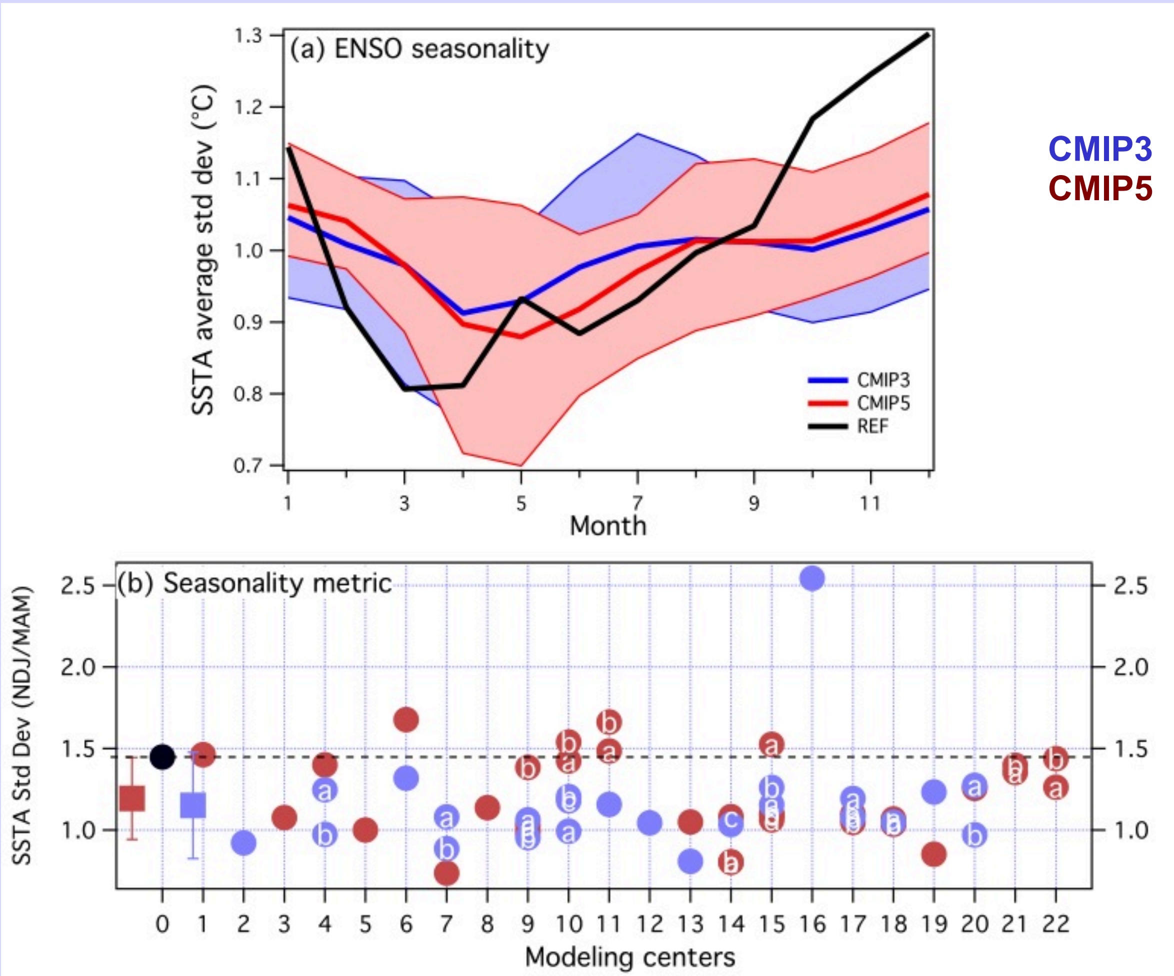




- Cold tongue extends too far west, opens the warm pool
- Zonal wind too strong in west Pacific
- CMIP5 shows improvement in west (30% reduction in cold tongue error)

Bellenger et al. (2013), Lee et al. (2013)

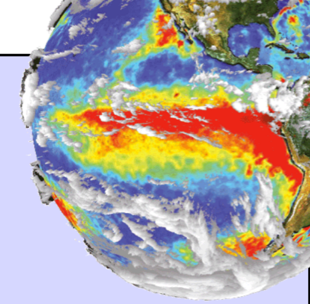
El Niño in coupled GCMs - seasonality



CMIP3
CMIP5

- Few models have the spring relaxation and the winter variability maximum
- Slight improvement in CMIP5

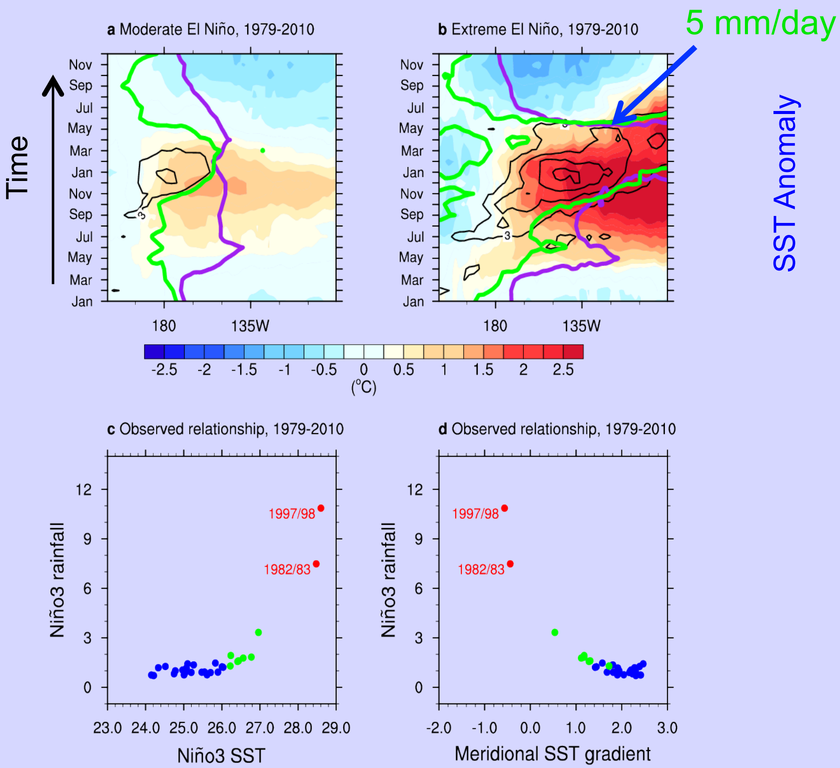
Bellenger et al. 2013



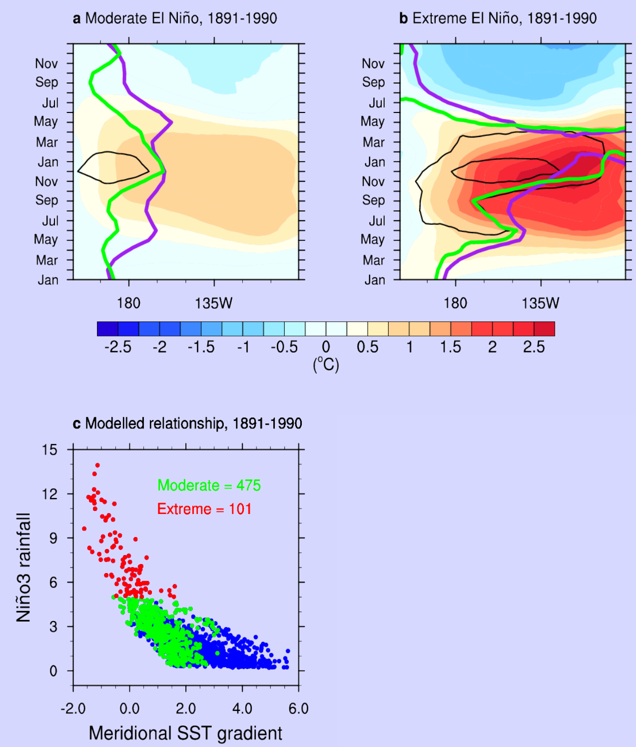
ENSO in a warming climate

Still no model agreement on mean amplitude change in future (IPCC AR5)
Extreme El Niños have the largest impact and distinctive SST gradients signature

Observations (1979-2010)

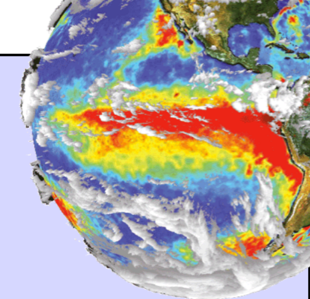


CMIP3 + CMIP5 models (select)



Cai et al. Nature CC (2014)

20^{th} C = 17% of extremes



ENSO extremes increase in a warming climate

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Extreme El Niños have the largest impact and have distinctive SST gradients signature

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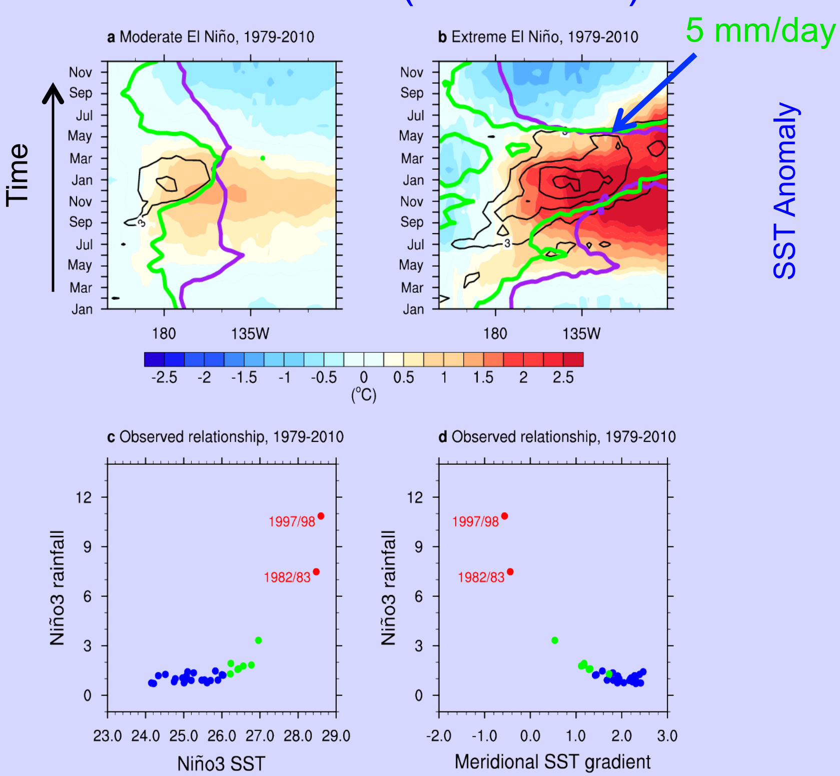
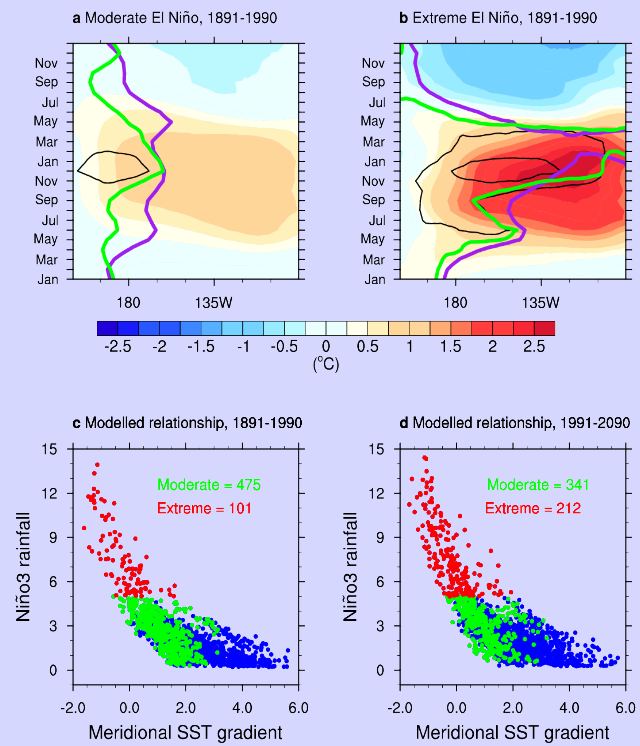


CMIP3 + CMIP5 models

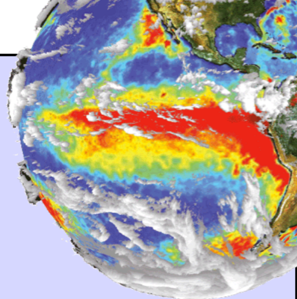


20th C = 17%   21st C = 38 %

Doubling of occurrence of extremes (RCP8.5)

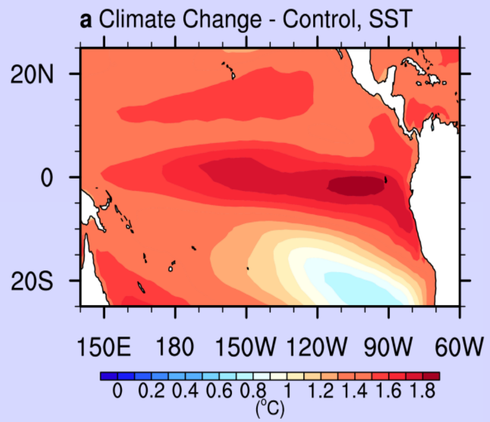
Cai et al. Nature CC (2014)

ENSO extremes increase in a warming climate



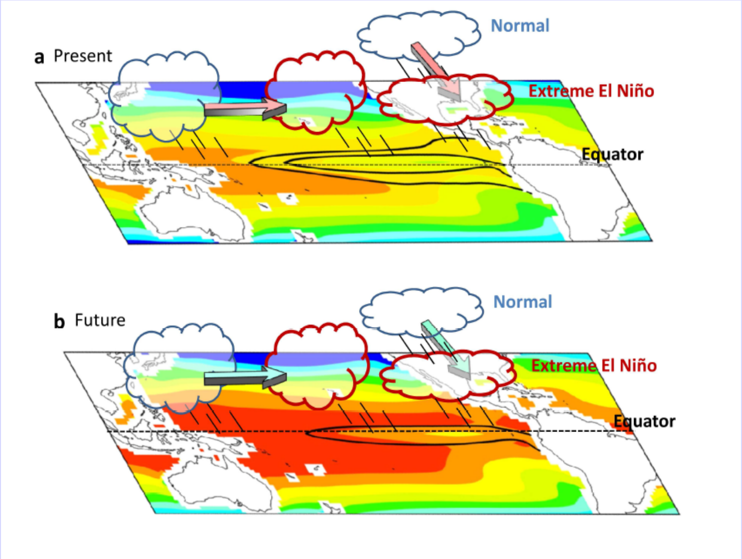
Projected surface warming over the eastern equatorial Pacific occurs faster than the surrounding ocean waters

→ Reduced meridional gradient of SST

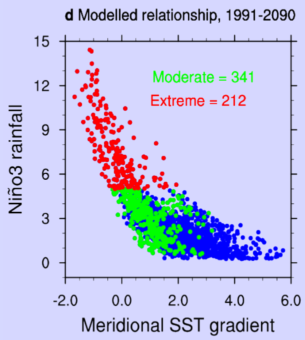


↓

More occurrences of atmospheric convection in the eastern equatorial region



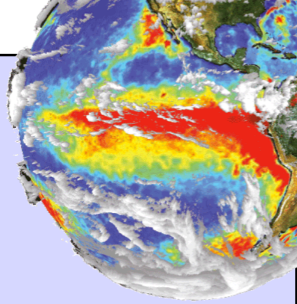
→ Increased occurrence of extreme El Niño



21st C = 38 % !!!

Cai et al. Nature CC (2014)

Process-based evaluation: key role of atmosphere during ENSO



Dominant role of AGCM in coupled AOGCMs

(Guilyardi et al. 2004, 2009, Kim et al. 2008, Neale et al. 2008, Sun et al. 2008, 2010)

The Southern Oscillation is an atmosphere-only mode

(Kitoh al 1999, Vimont et al. 2003, Chang et al. 2007, Dommenget 2010, Alexander et al. 2010, Terray 2011, Clement al. 2011)

e.g.: the Bjerknes coupled-stability index for ENSO I_{BJ}

Mean advection and upwelling (damping)

$$\frac{\partial\langle T\rangle}{\partial t} = 2I_{BJ}\langle T\rangle + F[h],$$

$$2I_{BJ} = -\left(\frac{\langle\bar{u}\rangle}{L_x} + \frac{\langle -2y\bar{v}\rangle}{L_y^2} + \frac{\langle H(\bar{w})\bar{w}\rangle}{H_m}\right) - \alpha$$

Negative heat flux feedback: α
(SHF, LHF)

Zonal advection feedback

Ekman pumping feedback

$$+\mu_a\beta_u\left\langle -\frac{\partial\bar{T}}{\partial x}\right\rangle + \mu_a\beta_w\left\langle\frac{\partial\bar{T}}{\partial z}H(\bar{w})\right\rangle$$

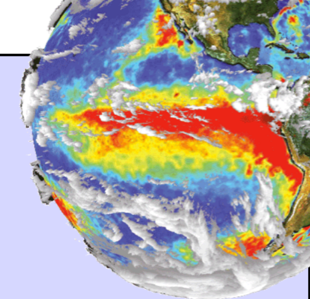
Dynamical positive Bjerknes feedback: μ

Thermocline feedback

$$+\mu_a^*\beta_h\left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle,$$

$$\beta_u = \beta_{um} + \beta_{us}, \quad F = -\left\langle\frac{\partial\bar{T}}{\partial x}\right\rangle\beta_{uh} + \left\langle\frac{H(\bar{w})\bar{w}}{H_m}a\right\rangle.$$

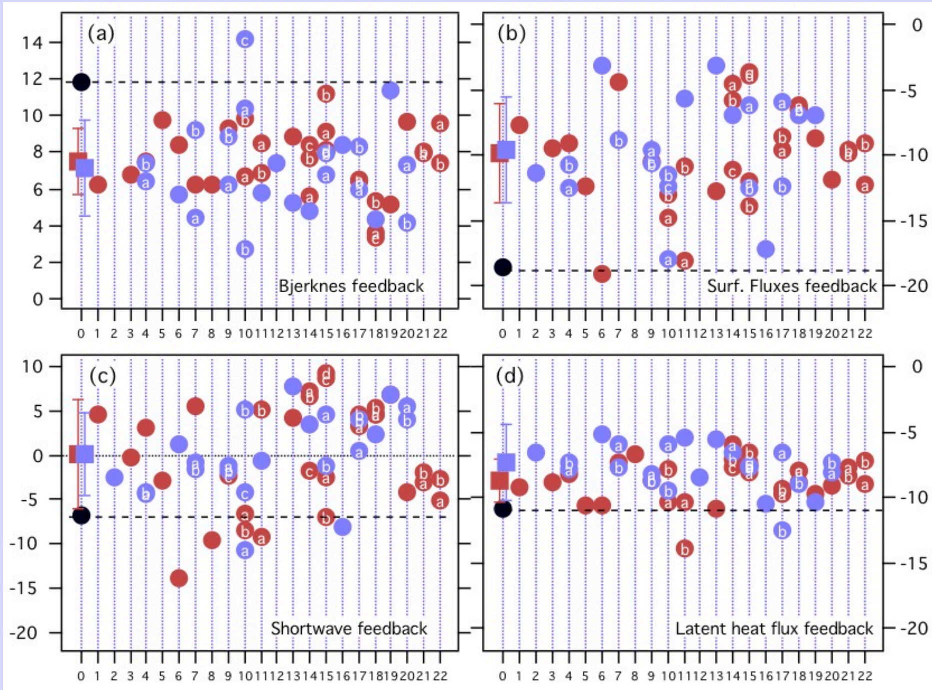
Linear stability analysis of recharged oscillator SST equation (Jin et al. 2006, Kim et al. 2010)



Atmosphere feedbacks in CMIP3/CMIP5

Bjerknes μ

α Total Heat Flux



SW Heat Flux α_{SW}

α_{LH} Latent Heat Flux

(W.m^2/C)

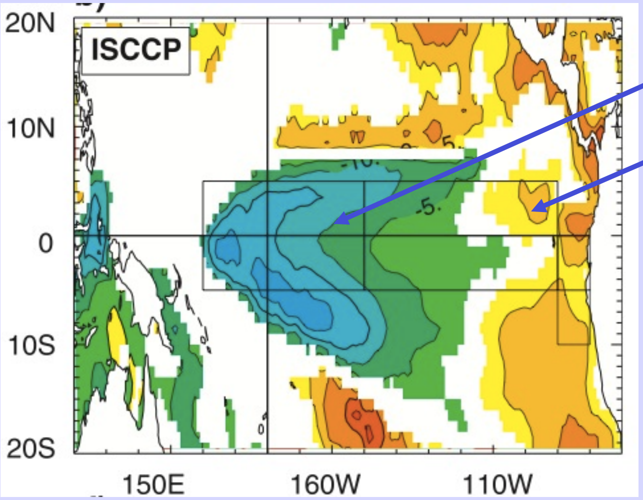
Models underestimate both μ and α (error compensation)

- Shortwave feedback α_{SW} main source of errors and diversity (sign change !)
- Errors in cloud response to dynamics and (low) cloud properties
- No clear evolution from CMIP3 to CMIP5

Bellenger et al. CD (2013),
based on Lloyd et al. (2011, 2012)

Source of α_{SW} errors

α_{SW} map (ISCCP)



Convective regime $\alpha_{SW} < 0$

Subsidence regime $\alpha_{SW} > 0$

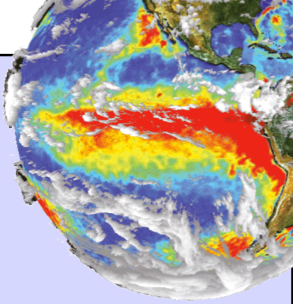
Both co-exist in Niño3

$$\frac{\partial SW}{\partial SST} = \frac{\partial \omega_{500}}{\partial SST} \times \underbrace{\underbrace{\frac{\partial TCC}{\partial \omega_{500}} \times \frac{\partial SW}{\partial TCC}}_{\text{AMIP}}}_{\text{Coupled}} \approx \alpha_{sw}$$

- α_{SW} error have their origin in the AGCM: cloud response to dynamics and (low) cloud properties

- When coupled, the dynamics also plays a role (SST drift)

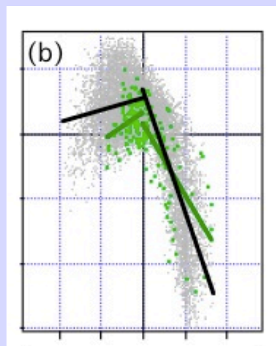
Lloyd et al. (2011, 2012)



Non-linearities in α_{SW} in East Pacific

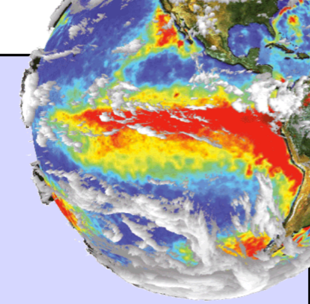
- Strong α_{SW} non-linearities in observations
- SSTA<0 Cold tongue **subsidence** regime $\alpha_{SW} > 0$
- SSTA>0 Warm pool **convective** regime $\alpha_{SW} < 0$

MIX



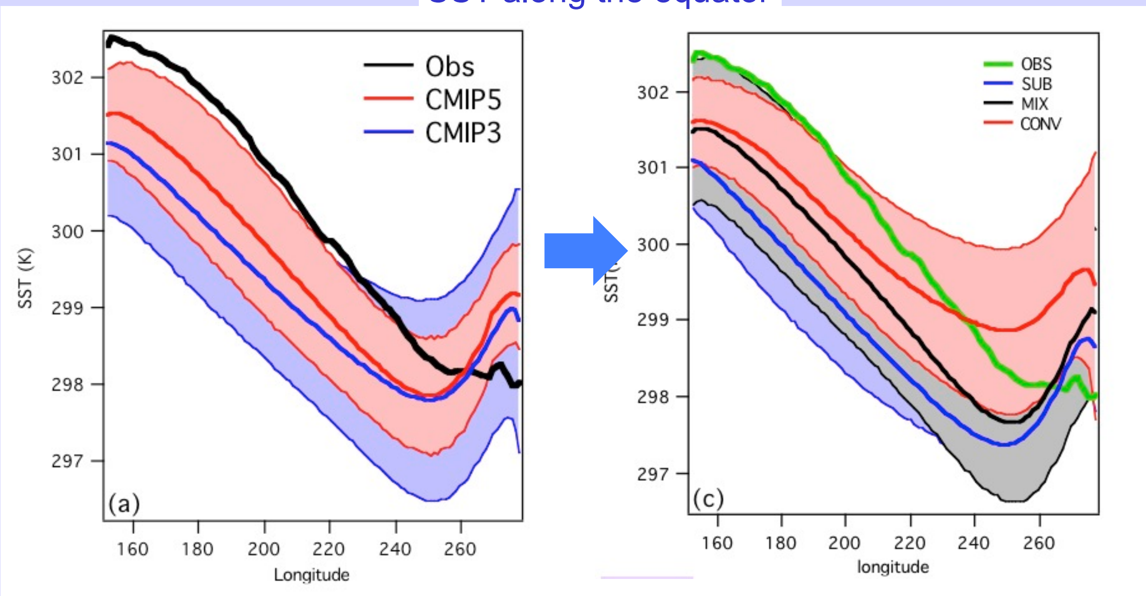
Observations (MIX)

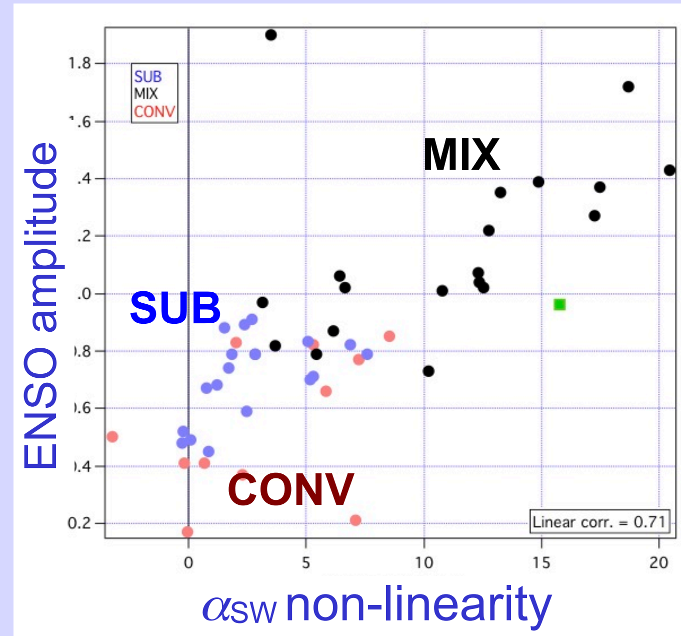
Non-linearities in α_{SW} in East Pacific



Classify CMIP3+5 models according to α_{SW} non-linearity

SST along the equator





MIX and CONV closer to obs in West Pac

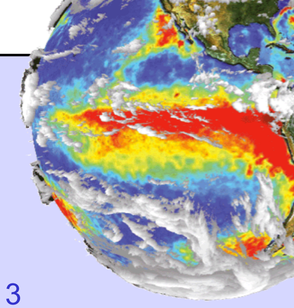
MIX has correct east-west slope

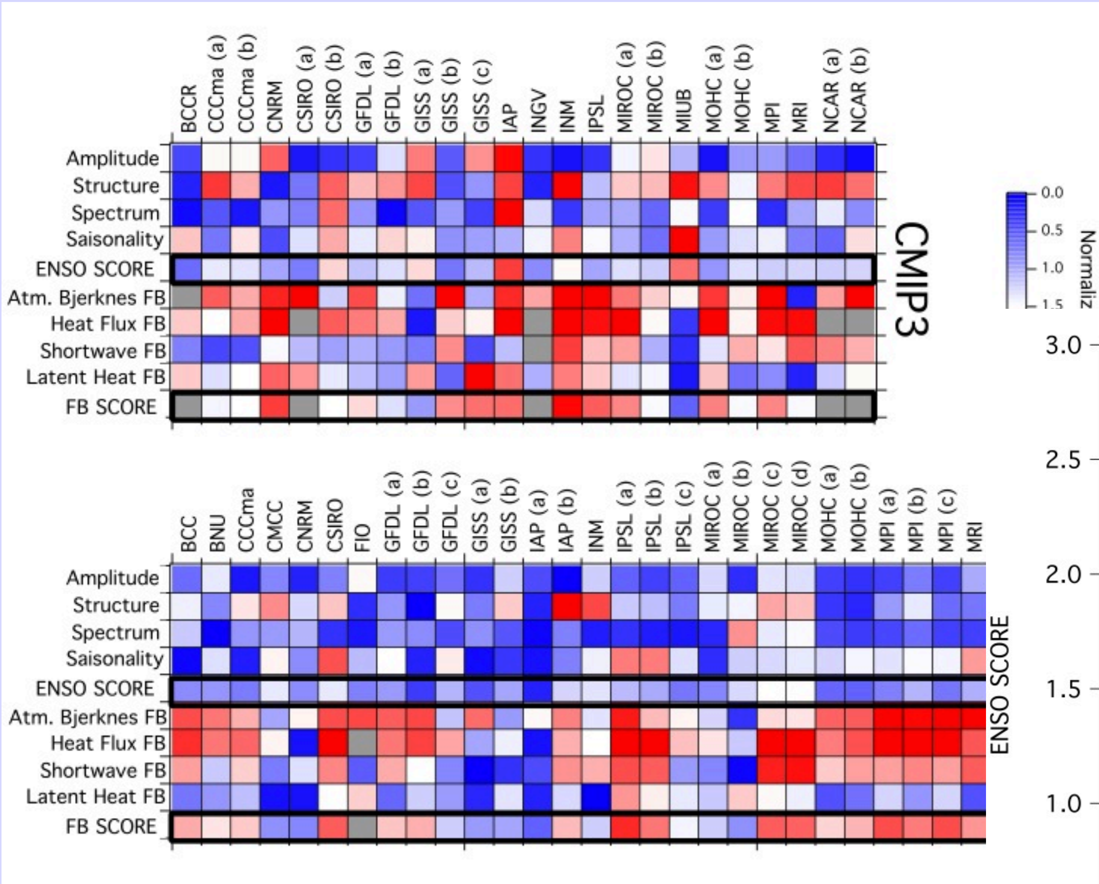
Only MIX models can have large ENSO amplitude (and extreme El Niños)

Bellenger et al. 2013

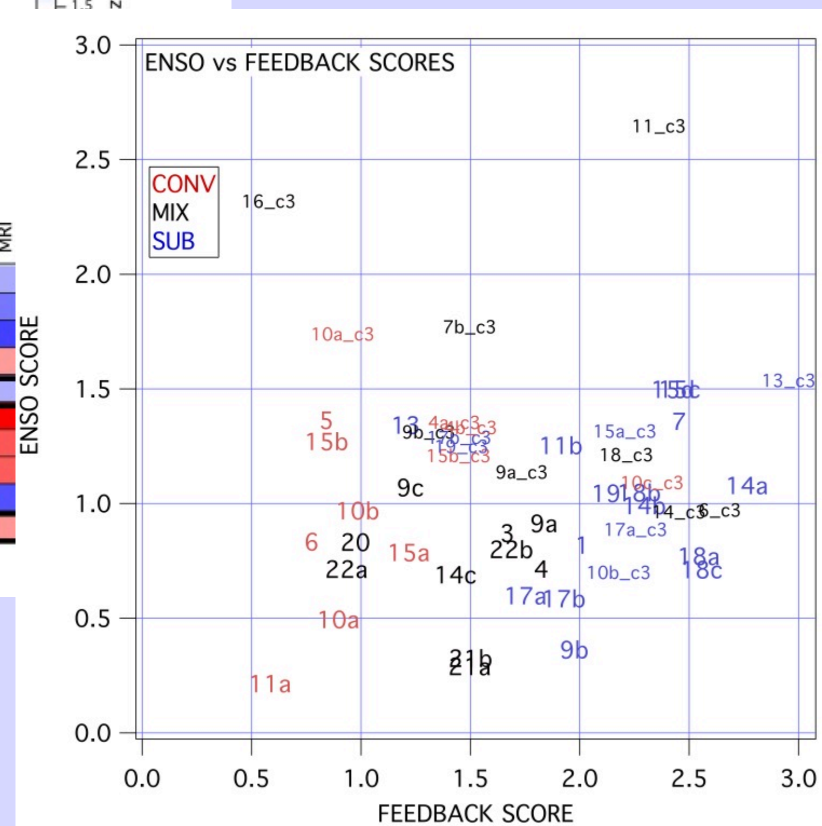
Better heat flux feedbacks, and ENSO, also come with better mean state

Performance vs. process-based metrics



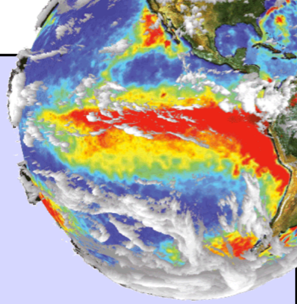


Bellenger et al. 2013



First indication of quality of models
No clear relation between ENSO stats and atmosphere feedbacks (need ocean feedbacks)

ENSO in CMIP5: summary



- Marginal improvement of ENSO statistics in CMIP5 vs. CMIP3
  - better mean state, less poor performing models, groups check ENSO stats
- Using rainfall= F(merid SST grad), scenario shows doubling of number of extreme El Niños in 21st century (RCP8.5)
- Poor modelling of ENSO feedbacks suggest that "improvements" in ENSO often result from error compensation
  - Little change from CMIP3 to CMIP5
- Large errors comes from SW heat flux feedback (role of clouds, convection and large scale circulation). Specific role of non-linearities
- Evidence that improving the mean and annual cycle will also lead to process-based ENSO improvement

Bellenger H., E. Guilyardi, J. Leloup, M. Lengaigne, J. Vialard (2013). ENSO representation in climate models: from CMIP3 to CMIP5. Clim. Dyn. ***42****, 1999-2018*

Cai W. et al. (2014) Increasing frequency of extreme El Niño events due to greenhouse warming. Nature Climate Change, ***4****, 111-116*